Medical Informatics Research at Georgia Tech : An Overview

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Abstract

The overall objective of this paper is to describe ongoing research programs in the Medical Informatics Laboratory in the Bioengineering Center of the Georgia Institute of Technology. Current research projects are highly interdisciplinary, spanning such areas as computer vision and image processing, artificial intelligence, and computer graphics and visualization. In general, the emphasis of the research programs is placed on the processing, interpretation, and display of biomedical imagery. These investigations, supported by an expanding academic program in bioengineering and performed in collaboration with medical researchers, are aimed at exploring basic issues in science and engineering while at the same time contributing practical solutions to a variety of problems in health care.

1 INTRODUCTION

Medical Informatics has been a rapidly emerging and increasingly important field over the last several years, as witnessed by the growing number of publications, conferences, and organizations devoted to this field. An inherently multidisciplinary endeavor, medical informatics benefits from, and contributes to, such areas as electrical engineering, computer and information science, bioengineering, and medical science. At the Georgia Institute of Technology, an expanding academic program in bioengineering and medical informatics [1] has been accompanied by a growing research program in these areas. A focal point of research in medical informatics is the Bioengineering Center in general, and the Medical Informatics (**MI**) Laboratory in particular. Within the MI Lab, research activities in medical informatics can be viewed as falling into three broad categories: (a) computer vision and image processing, (b) artificial intelligence, and (c) graphics and visualization. The research involves various imaging modalities, including X-ray, Nuclear, and Magnetic Resonance Imaging; clinical applications include cardiology, neuroanatomy, vascular flow, and bioeffects of radiation. The research is conducted in association with Emory University School of Medicine and numerous departments at Georgia Tech including the Schools of Electrical, Chemical, and Mechanical Engineering, and the College of Computing. In this paper, we present a summary of ongoing research at the MI Lab. References are provided to numerous publications that contain more detailed, technical discussions of the research summarized in this paper.

2 RESEARCH IN COMPUTER VISION AND IMAGE PROCESSING

The thrust of current research in the area of computer vision and image processing is directed toward the development of models and approaches to detect, recognize, analyze, and interpret medical imagery. The research concentrates on (i) Active contour models (or snakes), (ii) 3D arterial reconstruction, (iii) automatic determination of the orientation of the left ventricle from tomograms, and (iv) segmentation and analysis of temporomandibular magnetic resonance images.

2.1 Active Contour Models

Active contour models have shown themselves to be a powerful and flexible paradigm for many problems in image understanding. Active contour models [2, 3, 4, 5, 6] are being applied to the problem of detecting coronary blood vessels in cardiac angiography images, an important medical image understanding problem. Given a small set of initial points, active contour models ("snakes") are used to find coronary vessels, resulting in greater consistency and less computation than traditional vessel detection algorithms. The idea behind snakes is to redefine such computer vision problems in terms of energy-minimization. Thus energy-minimizing splines can be used to find image features such as minima or edges, and can be subjected to a variety of user-defined, externally-generated "forces" to assist the snake in finding the solution to the minimization problem. Mathematically, an active contour model is a spline $\mathbf{v}(s) = [x(s)\ y(s)]^T$ where $0 \leq s \leq 1$. Following the mathematical development of Kass [4], the energy of the spline can be defined as

$$E_{spline}(\mathbf{v}(s)) = \alpha(s)|\mathbf{v}_s(s)|^2 + \beta(s)|\mathbf{v}_{ss}(s)|^2 \qquad (1)$$

where $\alpha(s)$ and $\beta(s)$ are functions that control the elasticity and rigidity of the spline, respectively. The terms $\mathbf{v}_s(s)$ and $\mathbf{v}_{ss}(s)$ are the first and second derivatives of $\mathbf{v}(s)$ with respect to s. An additional energy functional $E_{external}(\mathbf{v})$ is defined which includes the influence of the image as well as other constraints. The overall energy $E(\mathbf{v})$ is defined as

$$E(\mathbf{v}) = E_{spline}(\mathbf{v}) + E_{external}(\mathbf{v}). \qquad (2)$$

Therefore, the functional to be minimized is

$$J(\mathbf{v}) = \int_0^1 E(\mathbf{v})ds. \qquad (3)$$

Figure 1. illustrates the application of snakes for single-frame coronary vessel detection. Snakes are also being emiguployed to detect vessels across multiple frames, a task which involves predicting the location of the snake in the current frame based on its location in previous frames. An interactive visualization tool for snakes which facilitated this work has also been developed using the windowing environment of **X**.

2.2 3D Arterial Reconstruction

One of the most difficult and interesting problems in biomedical research is the quantification and visualization of vascular structures. The aim of ongoing projects at the MI laboratory is to reconstruct the 3D vasculature from limited angiographic views from X-ray [8] or MR angiographic data [9]. The methodology involves the following steps: (a) Vascular structure detection and quantification from the 2D angiographic data; (b) Backprojection of detected features from multiple views (not limited to orthogonal pairs) to reconstruct the 3D vasculature by geometrical transformations [7]; and (c) Creation of a 3D computer model to quantify and visualize a shaded computer rendering (at any orientation) of the vasculature.

Before any arterial features are extracted, distortions in the acquired digital images are corrected. The vascular structure detection is achieved by tracking vessel segments and employing Laplacian of Gaussian and Entropy edge detection operators; Figure 2. presents the results of this feature extraction process. Once the 2D vessel geometry from each view is obtained, this information is organized and made available in a hierarchical database. The reconstruction algorithm is based upon the fact that the 3D coordinates of any point in a structure can be computed as the point of intersection of its back-projection lines. These 3D back-projection lines originate at the source of each projection and terminate at the point where the feature in the structure to be reconstructed is detected in the corresponding projection. The backprojection approach is illustrated in Figure 3. below. The final tasks in the reconstruction method are to output a graphical model describing the 3D solution and a quantitative summary describing the arterial structure. The vascular model is represented as a continuous set of generalized frusta defined as singularly curved sufaces connecting two elliptical ends. The quantitative summary includes estimates of vessel diameters and lengths.

This methodology is being applied to visualize and quantify, coronary vasculature from X-ray angiograms [8], the abdominal aorta from MRI data [9], and to the vasculature of the brain from X-ray angiography. Figure 4. illustrates the results of 3D reconstruction of coronary vasculature, Figure 5. presents a 3D shaded computer drawing of the reconstructed abdominal aorta, and Figure 6. displays preliminary visualization results of the cerebral vasculature.

2.3 Automatic Determination of LV Orientation

Rotational myocardial tomography after injection of Thallium-201 at peak exercise is an important non-invasive test for the evaluation of patients with suspected coronary artery disease and acute or prior myocardial infarction. After the transaxial data set for the cardiac region has been reconstructed using known filtered back-projection techniques [12], an operator or medical technician identifies the orientation of the long and short axis of the left ventricle (LV) by following a standardized protocol [11]. The aim of this project is to automate the process of determining the orientation of the LV, thereby overcoming any inter- and intra-observer variations. Research is ongoing to determine novel and robust methods to assist in the accurate and fast computation of the orientation of the LV using image processing and pattern recognition techniques. Some preliminary results [14] are quite encouraging.

2.4 Craniofacial MRI Analysis and Understanding

The long term objective of this project is to establish a methodology for obtaining, processing, and interpreting clinical tempromandibular joint (TMJ) studies using magnetic resonance imaging (MRI). The current research focuses on two technical issues : (a) optimizing the acquisition of MR images of the TMJ by observing the effects of systematically varying MRI system parameters and (b) subsequently processing these images to further aid in recognizing and characterizing TMJ structures. Edge-detection operators such as the entropy operator [13] and cluster-shade algorithms have yielded encouraging preliminary results to separate the TMJ disc from other tissue.

3 ARTIFICIAL INTELLIGENCE IN MEDICINE

Computer based image and signal interpretation and understanding represent one of the most challanging tasks in medicine. Two projects under way at Georgia Tech address some of these issues: (i) Knowledge-based interpretation of cardiovascular nuclear tomograms to assist in diagnosing coronary artery disease, and (ii) development of models of visual perception and reasoning in radiology.

3.1 Knowledge Based Interpretation of Myocardial Perfusion Distributions

A rule-based system has been developed for interpreting 3D myocardial perfusion distributions obtained from Thallium-201 tomographic images [12]. The first generation of such a knowledge-based system was successfully implemented and tested using the certainity factor model for handling uncertainity [15, 16, 20, 19]. The present, third generation system incorporates over two hundred heuristics for evaluating coronary artery disease from stress and delayed ("at rest") perfusion studies, and it also incorporates other patient-specific clinical information [10]. The knowledge base is also currently being evaluated for use with $Technetium^{99}$.

Figure 7. illustrates the information flow of this knowledge-based diagnostic system. The short-axis slices reconstructed from Tl-201 SPECT acquisition are mapped to a 2D-polar representation (Figure 8.). An automatic feature extraction program uses searching and edge-hugging techniques to identify and localize all existing perfusion defects in this polar presentation. These regions are then assigned a certainity factor value based on comparisons with data acquired for normal patients. Finally, this information is exported to the knowledge based system for diagnostic interpretation. The $Nexpert^{©}$ object-oriented expert system shell for implementing the system. The frame-like organization of the knowledge base is illustrated in Figure 9. The inference engine searches through this knowledge base to test the rules with respect to incoming facts. A backward chaining searching strategy is used by this inference engine. Various near-term goals, usually associated with each frame, are achieved as it progresses towards its overall objective of evaluating patient condition. The output from the expert system is a patient condition report which provides the relative certainity associated with the location and shape of each myocardial perfusion defect, as well as suggestions regarding the pres-

ence or absence, location, and character of each coronary lesion. Pilot studies have shown that the results agree very favorably with experts' interpretations. This system is currently undergoing testing and evaluation in an actual, routine clinical setting.

3.2 Decision-Making in Radiology

The current research in this collaborative project with the College of Computing is devoted to the development of a model combining visual perception and problem-solving paradigms to better understand the radiologist's reasoning process [21]. The aims of this project are: (a) to design a methodology for integrating perceptual processing with problem-solving processing, and (b) to develop a cognitively-based model of visual interaction, to be implemented in an intelligent radiological visualization system, utilizing knowledge-based perceptual strategies in the application of image processing techniques. Preliminary results of experiments on subjects involved in clinical diagnostic radiology, medical experts and residents at the Emory School of Medicine [22, 24] have provided the basic underpinnings of this model.

4 COMPUTER GRAPHICS AND VISUALIZATION

This area of research is aimed at providing interactive displays and functional renderings of multidimensional image data.

4.1 3D and 4D Visualization of Unified Multimodality Cardiac Imagery

A methodology for quantifying and visualizing multimodality cardiac imagery is under development [7]. This methodology unifies the physiological information derived from perfusion distribution levels in the left ventricular myocardium with the anatomical information of the coronary vasculature from X-ray angiography. The 3D arterial reconstruction of the coronary vascular structure [8] is registered onto the computer model of the 3D myocardial perfusion distribution [23] to generate a unified computer model of the left ventricle. The methodology associated with the visualizing and quantifying the 3D arterial structure has been discussed in a previous section.

Three dimensional myocardial perfusion data is reconstructed from acquired tomographic data using filtered back projection techniques. The short-axis slices to be quantified are determined manually by following a standardized protocol [11, 17]. Maximal count circumferential profiles for each slice from the most apical to to the most basal slice are computed automatically. Each such profile consistes of a set of maximal counts per pixel along the radius extending from the center of the LV to the limit of the radius of search. This information is employed to build the visualization model of the myocardial perfusion using hermite patches as the surface primitives in the geometric modeler **MAX** [18].

Using anatomical landmarks and known system geometries, the two 3D computer models of the coronary vasculature and the myocardial perfusion are integrated. A quick visualization can be obtained by viewing a wireframe model, while a surface rendering of the unified model provide a better display. One can optionally use single or multiple, diffusion- or speckle-based light sources along with Phong or Gouraud shading algorithms to further enhance visualization. The best visualization of this model is obtained by viewing an animation created by rendering the model at different orientations. Figure 10. illustrates the results of the unification of the mycardial model with the arterial model for a phantom study. This integrated presentation allows for quick evaluation of any interrelationships that may exist between structure (stenotic lesion) and function (hypoperfusion). This approach also provides quantitative information pertaining to structural dimensions to further assist in the medical diagnosis. Such a comprehensive, unified approach is expected to improve the medical decision-making process for diagnosis and prognosis by providing both quantitative and qualitative information in an interactive environment.

4.2 Visualization of EM-Bioeffects

Recently, the electromagnetics bioeffects group introduced visualization techniques into their studies of electromagnetically-induced heat deposition in biological tissues. Initial work produced a rendering of the electric field intensity within a homogeneous sphere illuminated by incident, continuous-wave fields at and near the resonant frequency of the sphere. The immediate goal is to progressively refine the model to include inhomogeneity and heat removal. Electric field intensity (E-field) distribution inside a homogeneous dielectric sphere (5cm radius) due to an incident uniform plane wave (500MHz, continuous wave) is illustrated in Figure 11. Relative field strengths are color-coded such that white represents the highest value and blue the lowest. In the upper left photo, the meridional plane of the E-field is shown, with the E-field vertically oriented in the plane of the photo and travelling to the right. The upper right photo shows the E-field distribution in the meridional plane of the magnetic field vector. The lower photo shows the portions of each of the planes in the upper views in relation to one another by the removal of a quadrant from the sphere. In future, the model will include pulsed electromagnetic fields, and more complex dielectric geometries, such as prolate spheroids and human forms.

4.3 Visualization of Neurophysiological Data

The advent of 3D imaging of the brain has been refined to depict specific nuclei and tracts. At even higher resolution, individual neurons of a few tens of microns in diameter are being depicted along with specific neuronal characteristics such as type of neuron, connections to output targets, chemical transmitter, and so on. At the Neuroscience Laboratory, the neurons of mammalian red nucleus have been imaged, and the input and output connections of each neuron are being studied [25, 26]. Efforts are underway to visualize these neurons and their interconnections in 3D (Figure 12.).

5 Conclusions

On the basis of our work, and that our colleagues and collaborators, we conclude that medical informatics offers powerful methods and techniques to process, visualize, and interpret medical imagery in a consistently accurate and interactive manner. New and innovative techniques of medical informatics may thus significantly improve the tasks of diagnosis, prognosis, and therapy in health-care.

Preliminary research activities are underway in areas other than the aformentioned, such as artificial intelligence techniques in analysis and interpretation of electromyograms, 3D human motion analysis, automatic segmentation of opthalmological images, virtual environments to simulate and rehearse clinical interventions, artificial intelligence applications in neonatal studies, knowledge-based integration of 3D multimodality imagery, and knowledge-based diagnostic interpretation of multiple cardiac imaging modalities.

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7 FIGURES

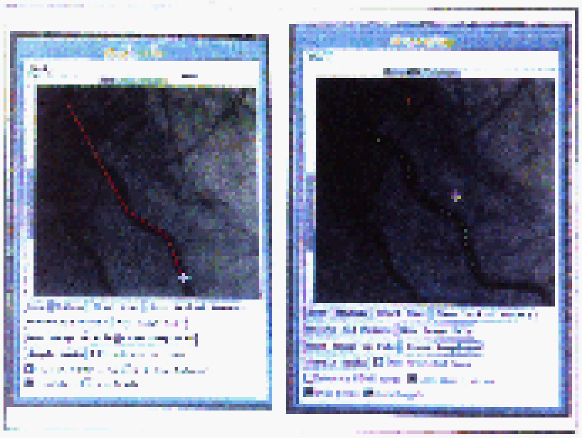

Figure 1: Single-Frame Vessel Detection after (a) 5, and (b) 15 iterations.

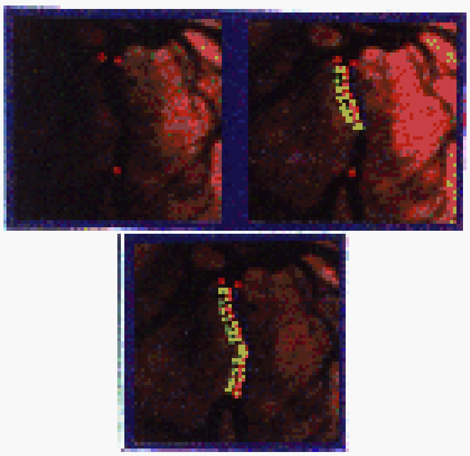

Figure 2: Illustration of Automatic Tracking Algorithm used for detecting coronary vessels from Angiographic views.

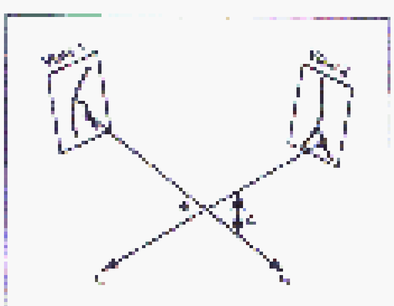

Figure 3: Back projected lines from biplanar images.

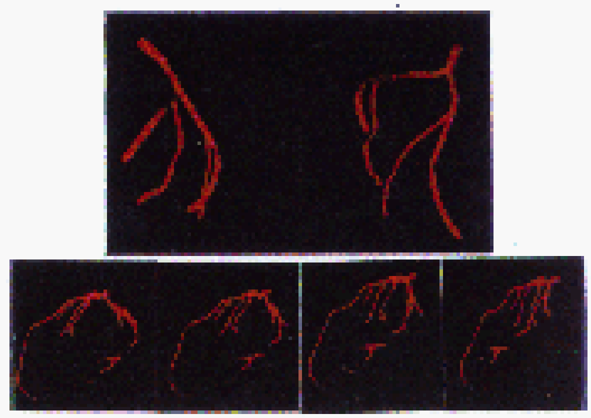

Figure 4: Shaded computer drawing of a reconstructed (a) copper phantom (b) 3D model of a patient's vasculature.

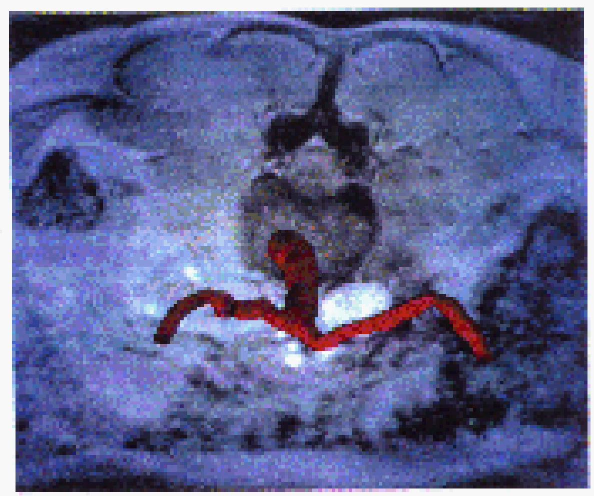

Figure 5: 3D shaded rendering of the Abdominal Aorta reconstructed from limited number of MR views.

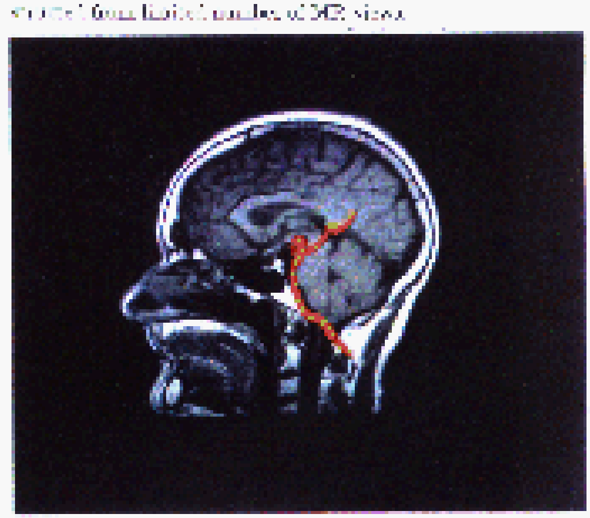

Figure 6: 3D Visualization of cerebral vasculature.

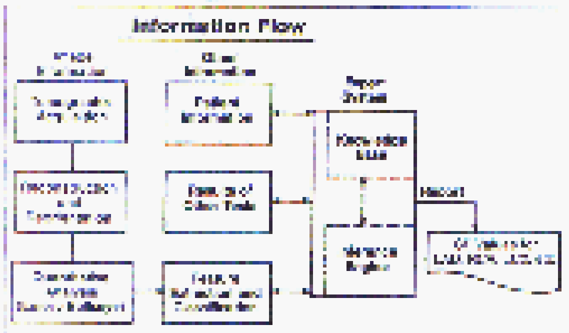

Figure 7: Information flow of knowledge-based system for interpreting thallium-201 myocardial distributions.

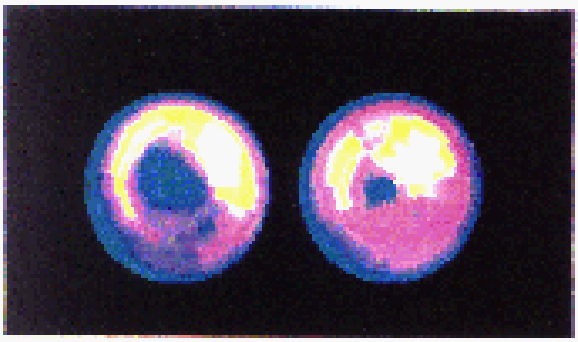

Figure 8: Stress and delayed bull's-eye color representations of 3D Thallium-201 myocardial distributions.

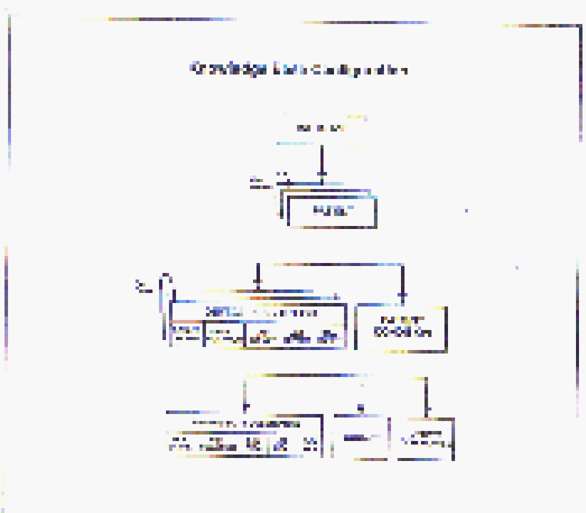

Figure 9: Knowledge base frame configuration.

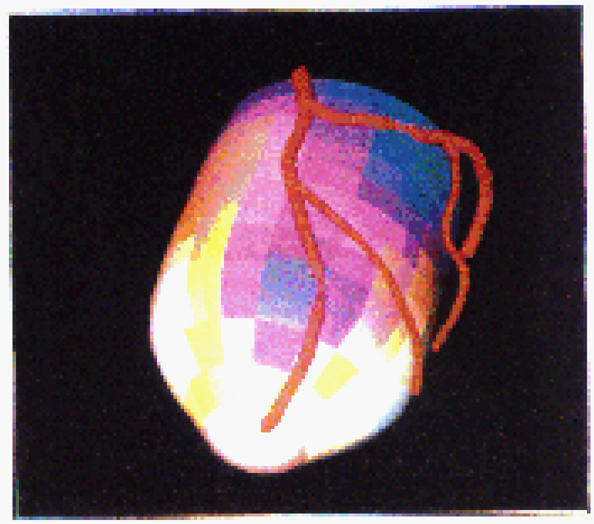

Figure 10: Visualization of fused anatomical and physiological information.

Figure 11: Radiation beam intensity (E-field) distribution inside a homogeneous dielectric sphere.

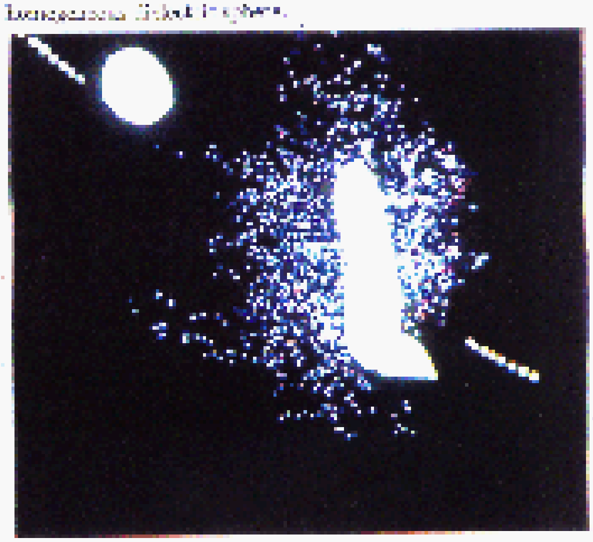

Figure 12: 3D visualization of neural interconnections.